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Low carbon effects of urban underground space

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ABSTRACT

Urbanization is progressing rapidly, while problems raised by climate change are occurring across the globe. Cities are at the center of both of the two tendencies therefore, low carbon or zero carbon cities are being promoted. Urban underground space (UUS) is a key component in the process of urbanization and plays a significant role in creating low carbon cities, as highlighted in this paper. Meanwhile, UUS also involves unavoidable drawbacks regarding energy consumption in terms of lighting, ventilation and dehumidification. In this paper, the advantages of UUS in creating low carbon cities are analyzed, and a framework for calculating the positive low carbon effects derived from UUS use is established. Additionally, some alleviating measures in response to the potential low carbon disadvantages of UUS are proposed. Based on the analysis, some planning and design implications for the development of urban underground space in order to fulfill its role as a contributor to urban sustainability are discussed.

1. Introduction

In recent years, extreme weather conditions worldwide, such as droughts, heat waves, extreme precipitation, flooding, wildfires, etc., seem to be occurring with higher frequency, some of which are increasing due to climate change to certain extent. The prevailing interpretation for such phenomena is the cumulative emissions of greenhouse gases, of which carbon dioxide is considered the most principal. Carbon dioxide contributes as much as 70% of all energy-related greenhouse gas emissions (Satterthwaite, 2008). Cities are at the center of the fundamental shift toward increased greenhouse gas emissions; however, the ever-increasing global urban population requires more energy consumption and thus generating additional potential greenhouse gas emissions. It can be concluded that cities can be regarded as both a problem and a solution for climate change (Popartan & Morata, 2017). In this context, low carbon city as a solution is widely accepted across the globe.

In parallel with rapid urbanization, urban underground space (UUS) is becoming more actively utilized, particularly in dense aggregations such as central business districts (CBDs) or downtowns, due to the increasing demand for urban space while ensuring ecological modernization. UUS will undoubtedly play a role, either positively or negatively, in the process of creating low carbon cities. For instance, in Chinese cities where low carbon strategies have been broadly adopted (Khanna, Fridley, & Hong, 2014; Yang & Li, 2013), UUS use is a key factor for urban development (Bobylev, 2016; Qiao & Peng, 2016; Zhao, Peng, Wang, Zhang, & Jiang, 2016) and urban sustainability (Bobylev, 2009; Sterling et al., 2012). However, even though the fact that urban underground space could be a contributor to low carbon cities has been widely acknowledged by academics (Delmastro, Lavagno, & Schranz, 2014; Yokotsuka, Matozaki, Kasuya, & Ohmura, 2014), many issues, e.g., how to measure its contribution and how will it guide UUS planning and design, have not been made explicit so far. Moreover, there is still a gap in the existing research with regard to the unavoidable drawbacks of urban underground space in energy consumption, e.g., lighting and ventilation. To bridge these gaps, in this paper, tentative research is carried out based on a case study of the Shanghai Hongqiao CBD. Here, the extent to which urban underground space would influence low carbon city development through both qualitative and quantitative measures of the low carbon effects of UUS is investigated. Additionally, the corresponding strategies of urban underground space planning and design to maximize the UUS advantages and to minimize the potential UUS disadvantages for sustainable low carbon cities are considered. It is anticipated that the findings of this research will assist future UUS development in achieving low carbon and sustainable cities.

2. Contributions of urban underground space to low carbon cities

In principle, there are two distinct approaches to achieve low carbon cities: ensuring a low carbon development pattern in key urban

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areas and stimulating the growth of the low carbon economy (Caprotti, 2017). With regard to the low carbon urban development pattern, existing research has primarily documented the following approaches to achieve the vision (Chan, Conejos, & Wang, 2017):

- High-quality public transportation and a pedestrian-friendly system
- Compact and mixed land use
- Renewable energy and an efficient energy system
- An efficient water provision and disposal system
- Intensive greenery and vegetation
- Smart growth and green infrastructures
- People-oriented cycling environment
- Improved road transportation mobility
- Community-level planning approach and delivery
- Low carbon community living education programs

Since it relates little to the direct market economy (Qiao, Peng, & Wang, 2017; Qiao, Peng, & Wang, 2019), urban underground space primarily contributes to cities by optimizing the planning, design and management of a functional and sustainable urban layout. The following sections detail the contributions of urban underground space to low carbon cities considering both the qualitative description and quantitative measurement. To better decipher how to fulfill the low carbon advantages of underground space and how to employ the quantification framework put forward in this paper, the case of the Shanghai Hongqiao CBD is introduced at the end of this section.

2.1. Qualitative analysis

There is much evidence in regard to what benefits urban underground space can contribute to addressing urban development problems and achieving urban sustainability (Bobylev, 2009; Qiao et al., 2017, 2019; Sterling et al., 2012). Low carbon city strategies could resort to these benefits as well, which include, but are not limited to, the following detailed aspects:

(1) Underground space enables urban transportation optimization. It has long been recognized that urban transportation, in particular the aforementioned features of high-quality public transportation, a pedestrian-friendly system, a people-oriented cycling environment, and improved road transportation mobility, is closely linked to low carbon cities. It is our contention that an efficient, comprehensive transportation system in low carbon urban core areas should consist at least of outer expressways, inner rail transit facilities, a parking system surrounding the business area, and a pedestrian network inside the business and commercial areas, which is abstractly called the "watermelon transportation model", as shown in Fig. 1. An outer expressway encircling urban core areas can separate arrival-departure and passing traffic flow, which can alleviate traffic pressure and increase road mobility. Rail transit lines running through the inner area can not only further reduce road traffic pressure but also, and more significantly, provide an eco-friendly trip mode. Shared and interconnected parking systems better serve motor vehicles and further ease transportation mobility by removing on-road parking. A pedestrian friendly passageway network around important metro stations connecting main buildings can give rail transit passengers and office workers a more comfortable experience during their trips to destinations.

Generally, urban underground space is the only alternative to and is a primary component of urban regeneration in built-up areas (ITA Working Group on Costs-Benefits of Underground Urban Transportation, 1990; Bobylev, 2010) when constructing expressways complementary to the existing expressway system, metro facilities, and separating pedestrians and vehicles, given that there is no extra space to accommodate such transportation facilities. Additionally, in newly built urban core areas, underground space can play an active role in untangling the complicated three-dimensional transportation system without damaging the cityscape.

(2) Underground space use favors compact city, mixed land use, smart growth, and increased greenery and vegetation. Compact city and mixed land use both serve low carbon cities as tools to reduce traffic volume, particularly that from motor vehicles. However, it is never an easy task for cities to achieve smart growth, that is, involving and adjusting to the changing needs of their occupants while effectively constraining the ever-increasing urban sprawl. In this regard, urban underground space is deemed, for most cases, to be an operative solution (Sterling et al., 2012) to alleviate the land use pressure for densely packed cities (Broere, 2016; Hunt, Makana, Jefferson, & Rogers, 2016; Sterling, 1997). More specifically, urban underground space can supplement commercial and business centers with retailing, shopping and dining uses, and facilitate the spatial integration of land parcels via underground connecting passageways. Thus, more land can be saved for urban amenities (Admiraal & Cornaro, 2016; Ronka, Ritola, & Rauhala, 1998; Sterling et al., 2012; Working Group No. 4, International Tunnelling Association, 2000) such as greenery and vegetation, public squares, and walking and cycling space.

(3) Underground space possesses green building and infrastructure potential. Underground buildings, most located within 30 m below the city, generally save more energy from heating and cooling (Bobylev, 2009) because the temperature of the shallow underground layer remains constant. At the same time, underground multiple utility tunnels consisting of heating, cooling, electricity, gas, etc. can boost the energy

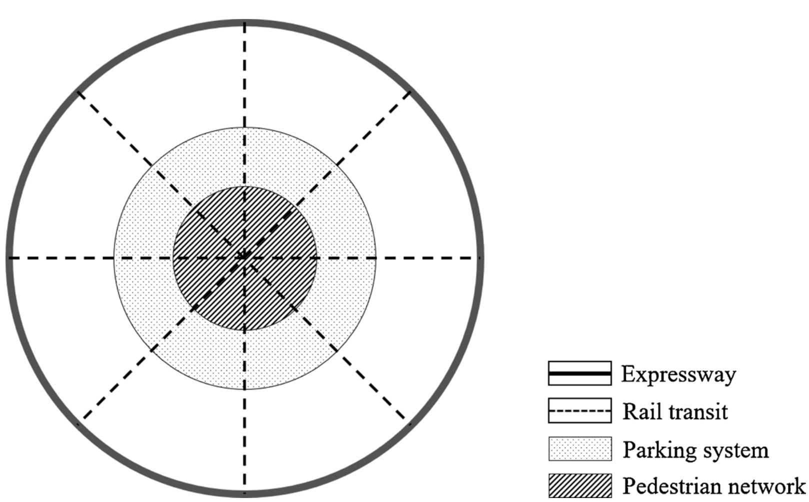

Fig. 1. Illustration of the "watermelon transportation model".
Modified from Qiao, Peng, Wu, and Ding (2018)

Table 1
Detailed calculation description of low carbon capacity indicators.

	Units of A_i	Units of TS_i and LS_i	Description of TS_i and LS_i
$i = 1$	[km]	[t/km]	Differential between rail transit and motor vehicles
$i = 2$	[pumps]	[t/pump]	Differential between shallow geothermal energy and fossil fuel energy
$i = 3$	[m^2]	[t/m^2]	Differential between underground and aboveground heating and cooling

Table 2
Energy consumption efficiency for different traffic mode types.

Modes	Energy sources	Consumption efficiency	Units
Light car	Gasoline	0.050	[(L·person^{-1})/km]
Taxi	Liquefied petroleum gas	0.142	
Heavy car and bus	Gasoline	0.016	
	Diesel oil	0.014	
Rail transit	Electricity	0.176×10^6	[(J·person^{-1})/km]

Table 3
Carbon dioxide transformation rate of gasoline and electricity.

Energy sources	Transformation rate	Units
Gasoline	2.2	[kg/L]
Electricity	0.997	[kg/(kW.h)]
	$0.997/(3.6 \times 10^6)$	[kg/J]

efficiency throughout the energy system including the supply, distribution and end use.

(4) Geothermal resources provide renewable energy. Geothermal resources are considered one of the most important underground resources along with physical space, groundwater, geomaterials (Bobylev, 2009) and historical resources. Despite accounting for only a very small share of current energy use, geothermal resources constitute immense potential of contribution to sustainable global development (Balat, Balat, & Faiz, 2009). Geothermal resources can be used either for generating electricity from deep geothermal energy buried at depths greater than 200 m or for direct uses, such as building cooling and heating and greenhouse heating, from shallow geothermal energy. Unlike the technically sophisticated deep geothermal energy exploitation, shallow geothermal energy buried within the top 200 m is readily accessible with respect to technical requirements and distribution. This resource is attracting increasing attention worldwide because shallow geothermal energy buried deeper than 10–20 meters beneath the surface, where the temperature remains constant, is a ubiquitous renewable green energy that can be easily extracted through ground source heat pumps (Admiraal & Cornaro, 2016; Li et al., 2016; Sterling et al., 2012). In general practice, underground space development provides an economically viable solution for the installation of heat pumps, which can be buried simultaneously with the construction of newly built building foundations.

2.2. Quantification of low carbon capacity

In this paper, low carbon capacity of urban underground space refers to the total amount of carbon dioxide (CO_2) reduced by urban underground space development. Since urban underground space can contribute to low carbon cities by various means including, but extending far beyond, the aforementioned four major aspects, it would be rather challenging to adequately incorporate all the aspects of the low carbon capacity of urban underground space. To simplify matters, only the aforementioned four aspects are considered in this research as the quantifiable contributors of urban underground space to low carbon cities. Given that the major components of the second contributor, i.e., compact city, mixed land use, and smart growth, are also related to transportation issues (Bobylev, 2009; Sterling et al., 2012), we incorporate the first two contributors as the low carbon capacity indicator Q_1 that relates to transportation effects. Likewise, Q_2 and Q_3 represent the low carbon capacity indicators associated with renewable energy and green building, respectively.

The overall quantification method of low carbon capacity indicators is comparing underground low carbon solutions with their corresponding traditional solutions. Therefore, the total amount of low carbon capacity (represented symbolically as Q_{total}), i.e., the aggregation of Q_i (i = 1, 2, 3, …, n; in this study, n equals 3), can be calculated principally by the following equation:

$$Q_{total} = \sum_{i=1}^{n} Q_i = \sum_{i=1}^{n} A_i \cdot (TS_i - LS_i) \quad (0)$$

where A_i is the amount of the ith underground low carbon solution, and TS_i is the unit carbon dioxide consumption generated from the traditional solutions corresponding to the ith low carbon capacity, while LS_i is the unit carbon dioxide consumption from the ith underground low carbon solution. It must be noted that the units of A_i as well as TS_i and LS_i vary with the low carbon capacity indicator Q_i, depending on the physical form of the urban underground space uses, e.g., a polygon type for underground basements, polyline type for metro lines and point type for underground substations. More detailed data descriptions of the three indicators are listed in Table 1, and the calculation processes of the three indicators are described further as follows:

(1) Low carbon capacity of underground transportation (Q_1)

Compact city means that people can rely more on public transportation rather than private cars because they can easily and comfortably reach their destination from their terminal stations within a walkable distance. Rail transit is a low carbon transportation mode compared with motor vehicles. Therefore, the indicator of Q_1 compares the carbon emissions of the two types of modes. However, motor vehicle mode can also be categorized into several types, such as light car, taxi, heavy car, and bus, whose energy sources and consumption efficiencies are listed in Table 2 according to the statistical findings of Huang et al. (2005) based on data from Shanghai, China. For simplicity, the light car is adopted to represent the motor vehicle mode to be compared with the rail transit mode because it is a more common commuting choice in

Table 4
Statistics of energy consumption of public buildings.

	Units	Office	Shopping mall	Hotel	Hospital	Theater	Others	Total
Quantity	Households	56	12	19	7	2	4	100
Total floor area	$10^4 \cdot m^2$	366.86	53.55	103.51	29.16	7.70	35.68	596.46
Proportion	%	61.5	9.0	17.4	4.9	1.3	6.0	100
Energy consumption efficiency	GJ/(m^2·year)	1.43	1.89	1.73	1.80	0.81	1.00	1.51

Fig. 2. Low carbon design effect of the Hongqiao CBD.

cities without rail transit transportation. It should be noted that the energy consumption efficiency listed in Table 2 is calculated by the number of riders; therefore, the passenger flow volume should be obtained prior to the quantification of Q_1.

The carbon dioxide generated by gasoline and electricity can be found in Table 3, adapted from Tu et al. (2012), in which the unit of carbon dioxide transformation rate of electricity is modified from [kg/(kW.h)] to [kg/J] in order to be comparable with Table 2.

In this manner, the equation for Q_1 can be expressed as follows:

$$Q_1 = A_1 \cdot (TS_1 - LS_1) = D_{com} \cdot [N_{ride} \cdot (ECE_{car} \cdot TR_{gaso} - ECE_{rail} \cdot TR_{elec})] \tag{1}$$

where D_{com} is the main commuting distance of the low carbon site [km]; N_{ride} is the number of riders of underground rail transit [persons]; ECE_{car} and ECE_{rail} are the energy consumption efficiencies of light car and rail transit, i.e., 0.050 (L·person^{-1})/km and 0.176×10^6 (J·person^{-1})/km, respectively, according to Table 2;and TR_{gaso} and TR_{elec} are the carbon dioxide transformation rates of gasoline and electricity, i.e., 2.2 kg/L and $0.997/(3.6 \times 10^6)$ kg/J, respectively, according to Table 3.

(2) Low carbon capacity of underground renewable energy (Q_2)

Irrespective of the carbon dioxide discharged in the construction process, shallow geothermal energy can be treated as green energy without carbon dioxide emissions for household heating and cooling. Therefore, LS_2 would be zero in this situation, and the equation for Q_2 can be expressed as follows:

$$Q_2 = A_2 \cdot TS_2 = N_{pump} \cdot (E_{ave} \cdot TR_{elec}) \tag{2}$$

where N_{pump} is the number of geothermal pumps [pumps]; $\mathrm{E}_{\mathrm{ave}}$ is the average amount of energy of each pump provided by the shallow geothermal energy for household heating and cooling [J/pump]; and TR_{elec} is the carbon dioxide transformation rate of electricity, i.e., $0.997/(3.6 \times 10^6)$ kg/J, according to Table 3.

(3) Low carbon capacity of underground green building (Q_3)

Underground building can be considered as green building because of its unique characteristic to sustain a constant and comfortable temperature, which can save a considerable amount of energy consumption for heating and cooling. According to the Design Manual for Heating and Air Conditioning of Underground Buildings (DMHACUB Working Group, 1983), the energy consumed for heating and air conditioning of underground buildings is approximately 10% that of surface buildings, which means that the carbon dioxide emission differential between underground and surface buildings in heating and air conditioning, i.e., the value of TS_3 minus LS_3, would be $0.9 \times TS_3$. In 2005, the Ministry of Housing and Urban-Rural Development of China (MOHURD) reported that the energy consumed for heating and air conditioning amounted to 60%–70% of total building energy consumption (MOHURD, 2005). Taking 60% as a conservative value, the remaining part of the quantification process for Q_3 is to identify the total building energy consumption. In this regard, Zhang, Lu, and Ni (2008) conducted informative research on the statistics of energy consumption of residential and public buildings in Shanghai. Since the energy consumption of underground buildings is dominated by the underground public service space, which is highly frequented by humans for purposes such as working, shopping, catering, accommodation, health care, and entertainment, we are more concerned with the data for public buildings as listed in Table 4.

Given that in real planning practice underground public service facilities are not generally categorized into such detailed uses, this paper adopts the average value of the energy consumption of public buildings, that is, 1.51 GJ/(m^2·year). Thereby, the calculation equation for Q_3 of can be expressed as follows:

$$Q_3 = A_3 \cdot (0.9 \cdot TS_2) = A_{pub} \cdot (0.9 \cdot 0.6 \cdot ECE_{ave} \cdot TR_{elec}) \tag{3}$$

where A_{pub} is the total floor area of the underground public service space [m^2]; ECE_{ave} is the average value of the energy consumption of public buildings stated above as 1.51 GJ/(m^2·year); and TR_{elec} is the same as in Eqs. (1) and (2), i.e., $0.997/(3.6 \times 10^6)$ kg/J.

2.3. Case study of the Shanghai Hongqiao CBD

The Shanghai Hongqiao CBD (hereafter referred to as the Hongqiao CBD) is one of the three pilot low carbon projects in Shanghai (den Hartog et al., 2018). The Hongqiao CBD is a newly built business district breaking ground in 2009, which was planned with nearly all of the low carbon characteristics mentioned in this section (Fig. 2). As a particular development focus, underground space in the Hongqiao CBD also plays a critical role in achieving low carbon strategies.

2.3.1. Transportation

The overall transportation system of Hongqiao CBD, as shown in Fig. 3, is in line with that proposed in Fig. 1. More specifically, three elevated express roads are responsible for the arrival-departure and passing traffic volume; three existing metro lines along with the planned airport express tunnel carry the major proportion of passengers to the Hongqiao CBD and Hongqiao Transportation Hub; underground parking garages allow more space on the streets; and an underground pedestrian network connects shopping malls, offices, hotels, car parks, and the transportation hub.

As the most principal means of public transportation, underground metro lines are anticipated to account for 40%–50% of the total passenger volume of the Hongqiao Transportation Hub, which is predicted to reach over 1.1 million passengers per day. Therefore, N_{ride} can be taken as 0.4 million passengers per day. The main commuting distance to the Hongqiao CBD is regarded to be the same as that of the Hongqiao Transportation Hub and, according to Liu et al. (2018), can be taken as the most accessible range of a 30-minute-metro distance; that is, D_{com} equals 10 km (Liu et al., 2018). Consequently, Q_1 is calculated with Eq. (1) to be 8.9×10^4 ton/year.

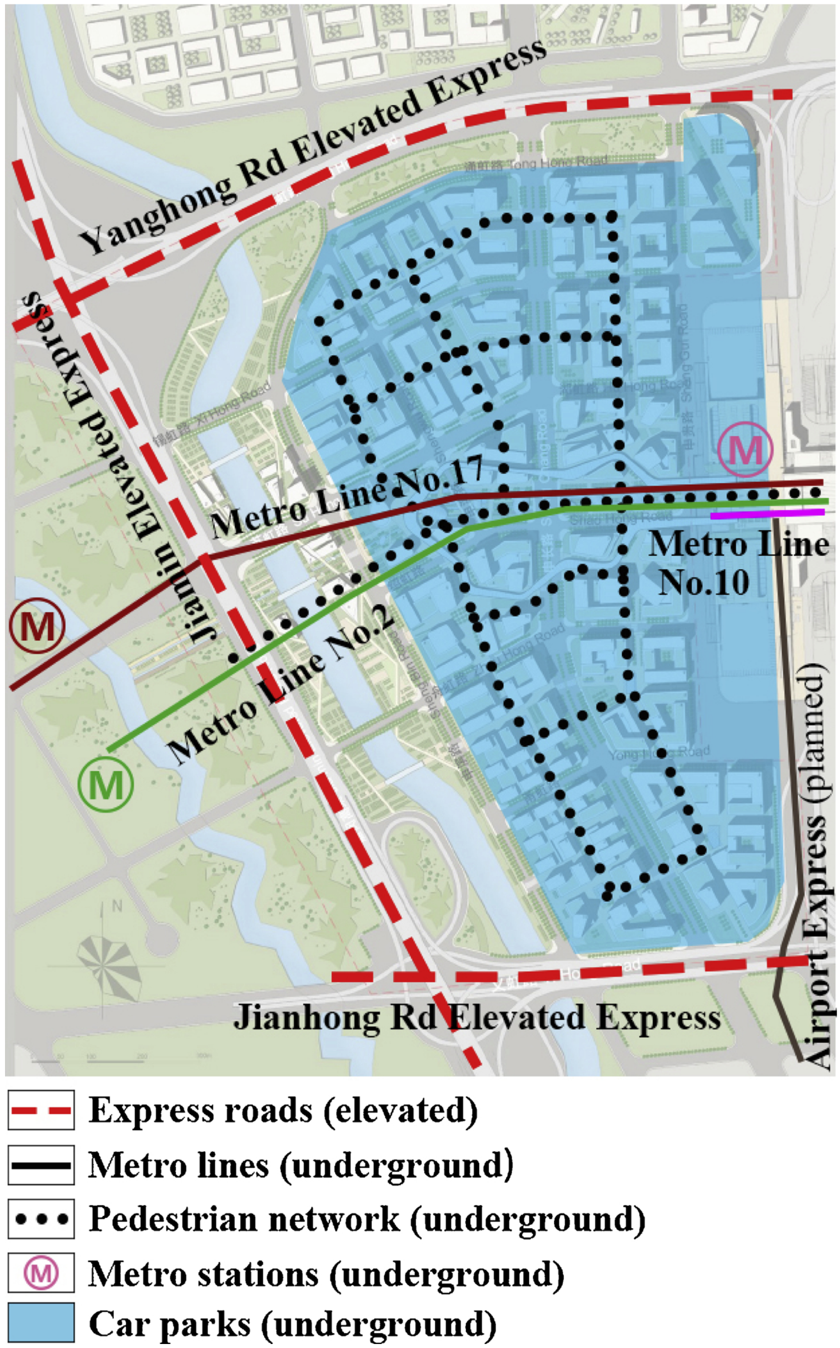

Fig. 3. Transportation system of the Hongqiao CBD.

2.3.2. Land use

Compact and mixed land use is an important factor for the Hongqiao CBD to achieve the low carbon city strategy. To a greater extent, it is the only way for the Hongqiao CBD to provide adequate space to accommodate the needs of intensive business and commercial activities due to the building height limit of 43 m due to the aviation considerations of the adjacent Hongqiao International Airport. Therefore, underground space below the Hongqiao CBD is intensively used not only to meet parking and municipal infrastructure demands but also to provide various public services, such as shopping, dining, and entertainment. According to the underground space planning of the Hongqiao CBD (Fig. 4), the total underground floor area of the public service space, that is, A_{pub} in Eq. (3), reaches 350,000 m^2, as listed in Table 5. Therefore, the calculation result for Q_3 from Eq. (3) is 7.9×10^4 ton/year.

2.3.3. Renewable energy

Shallow geothermal energy is estimated to provide for 20% of the energy consumption of the buildings in the Hongqiao CBD. Shallow geothermal energy is derived by pipes attached to cast-in-place building piles. According to the Report of Urban Design for Hongqiao CBD Core Area Phase I that was completed in 2010, the shallow geothermal energy system would reduce the emission of carbon dioxide up to 11.0×10^4 ton/year, which means Q_2 can be adopted as 11.0×10^4 ton/year.

3. Potential negative effects and the relevant alleviating measures

Even though underground space possesses green building potential, the unavoidable drawbacks of the underground space that are closely related to building energy consumption must be considered. Such

Fig. 4. Underground function layout planning of the Hongqiao CBD Core Area Phase I.

Table 5
Development amount of underground space in the Hongqiao CBD.

Facility type	Amount (m^2)
Public service	350, 000
Parking	470, 000
Metro tunnel	95, 000
Equipment	95, 000
Total	1, 010, 000

positive and negative effects of underground space use regarding low carbon effects are due to the binary nature of underground buildings. On one hand, the enclosed space beneath the surface surrounded by soil and rocks is an inherent advantage in maintaining a constant and comfortable temperature in underground buildings, thus reducing the energy consumption of heating and cooling. On the other hand, the enclosed space could also pose negative impacts on the quality of the interior environment of underground buildings, which generally requires more energy than surface buildings in terms of lighting, ventilation, dehumidification, etc. Despite the fact that the advantages of underground buildings far outweigh the negative aspects in terms of building energy consumption, the negative aspects should also be considered in order to maximize the prospects for the low carbon effects of urban underground space.

An enclosed environment may lead to negative psychological outcomes because it is dark, damp, confined, easily disorienting, poorly ventilated and reminiscent of death and burial (Shan, Hwang, & Wong, 2017). To overcome these drawbacks, the following aspects should be the priorities in the low carbon design strategies of underground buildings.

3.1. Lighting

In general, underground buildings lack natural light, which results in increased energy consumption for artificial lighting. Moreover, it may be associated with visual effects and impacts on the health of people remaining underground for a long period compared with those of occupants of surface buildings (Table 6).

It is apparent that the most straightforward response to this drawback is to introduce more natural light into underground buildings. Overall, natural lighting in underground buildings can be grouped into passive lighting and active lighting. Active lighting captures light from the surface and then guides it into underground buildings, such as a fiber-optic tube or mirror reflection. Passive lighting requires a certain architectural space in underground buildings to be created to catch sunlight, such as side window lighting, and zenithal lightning. Due to its higher economic feasibility, passive lighting is gaining more recognition. Among the methods of passive lighting, zenithal lighting via sunken plazas, concourses and skylights is more popular, which is widely adopted in the Hongqiao CBD, as shown in Fig. 5.

3.2. Ventilation

Due to the limited connection access to the surface, underground space is relatively enclosed from the atmosphere, thus impeding the ventilation of underground buildings. Poor ventilation leads to the accumulation of pollutants, increased dampness and further damage to people's health.

It is the general practice to enhance ventilation of underground buildings by mechanical means. Despite the energy consumption factor, mechanical ventilation cannot meet the fresh air demand for everyday activities. From this perspective, natural ventilation can aid mechanical ventilation in reducing energy consumption and supplementing fresh air. In this respect, the aforementioned passive lighting forms, notably

Table 6
Comparison between artificial lighting and natural lighting.

	Artificial lighting	Natural lighting
Energy consumption	More	Less
Health state	Insufficient spectrum is not good for health	Good for blood circulation, hepatic function, bone health, etc.
Visual effect	Lack of homogeneity and color rendering	Homogeneous, mild and rendering
Eye fatigue	Spectral frequency is low and easily results in eye fatigue	Spectrum of visible range is comfortable for eyes.

(a) Concourse (b) Skylight

(c) Sunken plaza

Fig. 5. Zenithal lighting examples in the Hongqiao CBD.

Table 7
Summary of the quantitative results of the low carbon effects in the Shanghai Hongqiao CBD.

	Underground rail transit	Underground geothermal energy	Underground building energy consumption	Total	Units
Low carbon capacity (tons/year)	8.9	11.0	7.9	27.8	10^4 ton/year
Proportion	28.4	39.6	28.4	100	%

sunken plazas as shown in Fig. 5, can provide excellent air circulation for underground buildings.

4. Discussion and conclusions

In this paper, the low carbon effects of urban underground space are analyzed, both qualitatively and quantitatively. Urban underground space mainly contributes to creating low carbon cities with regard to transportation optimization, compact and mixed land use, green building and infrastructure, and renewable geothermal energy. To simplify the quantification process, these low carbon contributions are categorized into underground rail transit, underground geothermal energy and underground building energy consumption. The quantification results for the low carbon effect of each category, for the case of

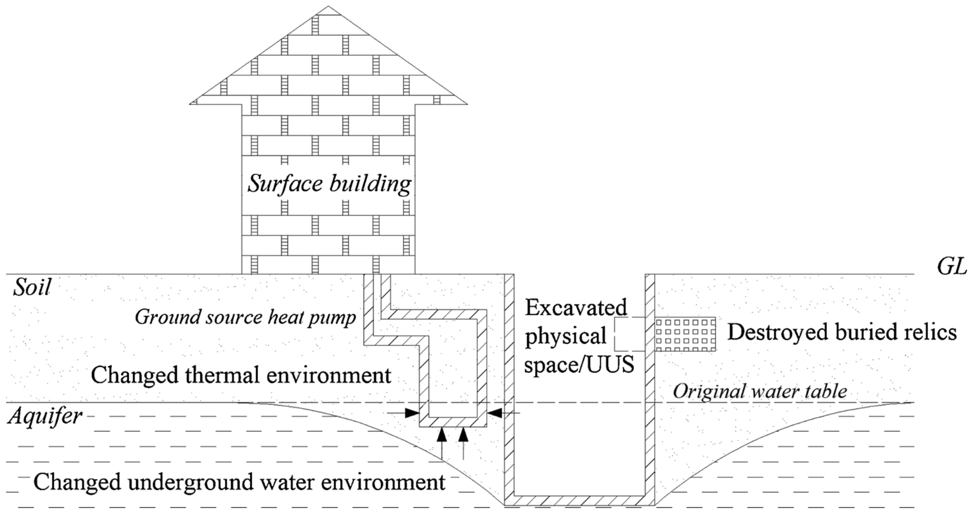

Fig. 6. Illustration of the potential impacts that UUS development may impose on shallow geothermal energy exploitation (Qiao, Peng, Liu, & Zhang, 2018).

the Shanghai Hongqiao CBD in Section 2.3, are documented in Table 7. The results show that urban underground space can aid in reducing carbon dioxide emission up to 27.8×10^4 tons every year, which is not an insignificant reduction in greenhouse gas emissions. However, it should be noted that the data employed in the case of the Shanghai Hongqiao CBD are just planning data, and the implemented underground volume is much larger, which means that urban underground space can contribute more to low carbon cities.

From the feedback interviews conducted by den Hartog et al. (2018), it can be found that the low carbon advantages derived from urban underground space in the Shanghai Hongqiao CBD are basically accomplished, especially in regard to lower ground traffic volume, increased greenery, etc.

Nevertheless, urban underground space also has drawbacks in building energy consumption for lighting and ventilation, and this should be considered because it is concerned with not only low carbon city but also the sustainable use of underground buildings.

For future urban underground space use that will be integrated with low carbon city goals, we conclude with some planning implications that may be applicable to other cities or projects:

- Urban underground space can play a balancing role in ensuring urban economic growth and achieving low carbon strategies, especially in densely populated cities.
- In particular, low carbon cities should prioritize urban underground space use from the following three planning perspectives. First, public transportation is the priority with particular emphasis on the underground pedestrian network, underground metro facilities and underground parking system. Second, shallow underground layers, notably the first two layers, can complement urban functions and contribute to compact city. Finally, geothermal energy is an ideal green energy replacement for traditional energy alternatives.
- Lighting and ventilation are the drawbacks of urban underground space both in achieving low carbon strategies and sustainable use. To address this issue, sunken plazas should be actively utilized in the planning and design process.

However, the findings in this paper do not imply that the low carbon capacity derived from urban underground space use would increase with the amount of urban underground space, since we did not incorporate the carbon emissions induced in the construction process and the potential threats to other underground resources. Not least potential threats, UUS development will undoubtedly impose impacts on geothermal energy exploitation through direct and indirect interfaces. As shown in Fig. 6, there is a high possibility of latent conflicts between physical underground space use and shallow geothermal energy exploitation, which would jeopardize the underground thermal environment due to the altered heat conduction medium (i.e., soil, rock) and groundwater flow (evidence can be found in the research of Zhang, Zhang, Yu, Guo, and Hao (2016)), and may further compromise the sustainable use of geothermal energy. Countries such as China that emphasize both urban underground space use and geothermal energy exploitation are particularly vulnerable to this critical risk. Therefore, urban underground space in low carbon cities should be planned and used based on underground space resource evaluation and demand forecasting (Peng & Peng, 2018a, 2018b).

Therefore, future research efforts should pay more attention to the reciprocal mechanism among underground resources, notably the interrelation between underground space use and shallow geothermal energy exploitation in low carbon city development, because it is closely connected with urban sustainability. In addition, the quantification of low carbon capacity derived from underground space use should be further detailed to increase the awareness of decision-makers. At the same time, planning and design methods and criteria for taking full advantage of the underground low carbon potential need to be refined and standardized so that they can be more practically applied by the urban underground space industry.

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